

MOBIUS: MOdelling BIOlogy Using Smart materials

F61775-02-WE014 AWARDED MARCH 22 2002

OVERVIEW AND AIMS

The research was to employ both computational models and "smart" materials. It was anticipated that such investigation would lead to significant advances in self-designing, self-assembling, self-repairing devices. In more detail, the aims of the research were:

1. To investigate the use of computer models of evolution and development to design and exploit intrinsic properties of novel materials.
2. To investigate the engineering potential of computational biology and novel materials by evolving self-designing, self-assembling devices.

SUMMARY

MOBIUS funding provided support for 50 percent of the time of Dr Peter Bentley over a three-year period from April 2002 to 2005. Work focussed in two main areas as identified in the aims: (1) the creation of novel computer algorithms, based on biological processes of evolution and development (embryogenesis) and (2) the creation of a novel robot which exploits novel materials such as shape memory alloys and rapid prototyping technology.

Results:

1. Several novel computer algorithms have now been developed during the course of this research. These are listed below:

- *The Fractal Development Algorithm.* This is an extension to a genetic algorithm, incorporating ideas of genetics and protein regulation into the process. The algorithm increases evolvability (the ability to find good solutions to problems) and has been shown to perform function regression and robot control with great accuracy. The algorithm also incorporates fault-tolerance into its evolved solutions, i.e., solutions withstand damage better than other evolved solutions.
- *The Fractal Immune System.* This is an extension to an artificial immune algorithm, incorporating ideas of protein regulation into the process. The algorithm performs dynamic clustering of data, and can learn (through an evolutionary strategy) to alter the way data is clustered to satisfy different classification requirements.
- *The Tissue Algorithms.* Two algorithms based on the way in which cellular growth occurs have been developed. These perform dynamic clustering and are intended to be used with artificial immune algorithms for tasks such as intrusion detection.

2. Early work on a novel "snake robot" resulted in the supervision of a doctorate student, Siavash Haroun Mahdavi, sponsored by BAE Systems (formally British Aerospace). As such, the robot equipment is owned by BAE Systems, but research findings of Peter Bentley are generated for the purposes of EOARD and the MOBIUS project. The following findings have been made:

- A snake robot using Nitinol (shape memory alloy) actuators can be controlled using an evolved finite-state-machine.
- Damage to the actuators of the snake robot, which detrimentally affects the motion of the robot, can be automatically overcome by the control software.
- An adaptive antenna, also using Nitinol actuators can be controlled using an evolved finite-state-machine, and minimise noise reception.

Dissemination:

(1) The novel computer algorithms resulted in 10 scientific publications, contributed to a book ("On Growth, Form and Computers" edited by Peter Bentley), and helped create several documents outlining future needs and requirements in the area (including a feature in *New Scientist*).

(2) The novel robot resulted in a further 5 scientific publications, several articles in *New Scientist* and *The Economist*, and is due to be shown in the robot section at the Royal International Air Tattoo, 2005.

Representative publications are included in the appendix of this report, in order to provide full technical details and research findings.

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY)		2. REPORT TYPE Final Report		3. DATES COVERED (From – To) 1 June 2002 -	
4. TITLE AND SUBTITLE Modeling Biology using Smart Materials (MOBIUS)			5a. CONTRACT NUMBER F61775-02-WE014		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Dr. Peter J Bentley			5d. PROJECT NUMBER		
			5d. TASK NUMBER		
			5e. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University College London Gower Street London WC1E 6BT United Kingdom				8. PERFORMING ORGANIZATION REPORT NUMBER N/A	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) EOARD PSC 802 BOX 14 FPO 09499-0014				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) SPC 02-4014	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT This report results from a contract tasking University College London as follows: The research will focus on two goals: (1) The creation of a new biologically-inspired algorithm that exploits both evolution and processes of development to enable computers to automatically find solutions to large-scale, complex problems, overcoming current scalability problems in evolutionary computation. (2) The demonstration of this algorithm on a novel combination of 'smart materials' (such as memory shape alloys and rapid prototyping technologies) for the design of self-adapting forms.					
15. SUBJECT TERMS EOARD, Advanced Computing, Artificial Intelligence, Biomaterials, Mathematical Modeling					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18, NUMBER OF PAGES 7	19a. NAME OF RESPONSIBLE PERSON Neal D. Glassman
a. REPORT UNCLAS	b. ABSTRACT UNCLAS	c. THIS PAGE UNCLAS			19b. TELEPHONE NUMBER <i>(Include area code)</i> +44 (0)20 7514 4437

RESEARCH PERFORMED

In this section an outline of the major research performed as part of MOBIUS is provided. For complete technical details, please refer to the publications provided in the appendix.

The Fractal Development Algorithm

Natural evolution and processes of development (e.g. embryogenesis) are exemplars of self-designing, self-building, highly adaptive and fault-tolerant systems. The genetic algorithm (GA) is a well-established search and optimisation algorithm based on natural selection. But on its own it does not have the capabilities observed in natural systems. In this work, motivated by the need to enhance the capabilities of GAs, a novel algorithm based on biological development was created. In this algorithm, parameter values are no longer coded as genes and evolved (as is traditional in standard genetic algorithms). Instead, genes define specific models of proteins, which interact with each other and the genes in a complex gene regulatory network.

In biology it is well known that complex interactions between an environment and a developing organism are crucial to ensure the correct development of that organism. Such interactions occur at all scales, from the movement of limbs, which ensures proper musculature and bone formation to chemical interactions between DNA, RNA and proteins, which ensure proper cellular development. In a very real sense, DNA has no meaning unless in the right environment. Information is derived from the chemical structure of the molecules and the subsequent myriad interactions of the environment around the molecule. This work hypothesises that such a complex environment is a prerequisite to the evolution of complex and useful genetic structures.

In an attempt to encapsulate some of this complexity without imposing an excessive computational overhead, proteins in the model are defined as subsets of the Mandelbrot Set. By allowing these fractal proteins to interact according to their shapes, a complex fractal chemistry is formed. The protein interactions are then used to control the development of solutions built from cells, akin to embryogenesis in nature. This provides significant advantages, which have been demonstrated experimentally:

1. **Evolvability is improved.** The ability of an evolutionary algorithm to optimise solutions to problems without becoming “stuck” in local optima, is improved. This is because of the structure of the fractal space being searched by the genetic algorithm – it has self-similarity so that a specific protein shape may be found in many different places; it is gradual, so that a small change to a gene will produce a correspondingly small change to the protein shape; it is infinite, so that there is no end to the variations of proteins that may be invented and exploited by evolution.
2. **Scalability is improved.** The representation is capable of performing tasks such as function regression of increasing complexity without requiring the developer to add problem-specific knowledge or heuristics. Indeed, the system has been shown to learn concepts such as modularity and reuse, should these assist it in solving a task. Developmental algorithms are increasingly showing promise in this area as they incorporate automatic module discovery and reuse allowing solutions of increasing complexity to be defined from evolved genomes of the same size.
3. **The ability of the system to find complex solutions to problems is improved.** The system has learned to control a bug-robot both with and without sensor input, giving it complex behaviour through an environment. In more detail, the evolved fractal gene regulatory networks underlying the controllers can be remarkably complex, incorporating features of fault-tolerance.
4. **Fault-tolerance emerges naturally in the system.** Sustained evolution fine-tunes the fractal proteins used in the developmental system, improving the efficiency of the solution, and adding redundancy to help protect the solution from damage. This happens because of the evolvability of the system – evolution never stops adapting the fractal proteins that form the gene regulatory networks. Once a perfect solution has been found, evolution can only damage such a solution, so it then reduces its size (so there is less to be damaged) and adds redundancy to ensure that a future mutation will not prevent the solution from working.

This leads to the following features:

- ❑ The fractal developmental algorithm can automatically produce complex solutions to hard problems (e.g. software or robot controllers can be generated)
- ❑ The solutions are efficient and capable of tolerating damage (if the software or the robot controller is corrupted, the solutions exhibit graceful degradation)

The Fractal Immune Algorithm.

The previous algorithm focussed on gene-protein interactions within a single cell. An alternative algorithm was created to investigate similar interactions in a multicellular model, in this case in an artificial immune system. This work was supported by BAE Systems (formally British Aerospace) who funded a graduate RA to work under the supervision of Dr Peter Bentley.

The immune system relies on protein and cellular interactions to function correctly. In immunobiology, proteins of interest are *antigens* (molecular markers used by the body to identify harmful pathogens), *antibodies* (proteins designed to recognise and in some cases disable the antigen and corresponding pathogen), and *cytokines* (proteins used as signals sent from one immune cell to another). The field of artificial immune systems specialises in modelling aspects of the human immune system for applications such as data mining, intrusion and virus detection, robot control and dynamic clustering.

In this work, an existing algorithm developed by colleague Dr Jon Timmis was extended. The *artificial immune network* models an input data stream as antigens, automatically forming “artificial recognition balls” (an abstract notion of B-cells and antibodies) to represent the data. The algorithm is, in effect, a dynamic clusterer, proven to cope with noisy and unpredictable data in real time. The extension to this algorithm, the *fractal immune network*, incorporated previously discussed fractal proteins into the method. Data is thus mapped to fractal antigens, recognised by fractal recognition spaces, and communication (network maintenance) is performed using fractal cytokines.

An evolutionary strategy is employed to evolve the mapping from data to fractal antigens, thus enabling different aspects of the data to be exploited during clustering, and allowing clustering to be tailored to perform a desired classification task. The work was preliminary, but demonstrated the validity of the approach – an automatically adapting dynamic clusterer can be constructed using these methods.

Tissue-Growing Algorithms.

The idea of multicellular development was investigated further with the creation of two new dynamic clustering algorithms. Designed for the task of anomaly detection, both algorithms accept a data stream as input, and “grow” a tissue representation, to cluster and hold that data for use by another application. In addition, both algorithms automatically detect anomalies in the input stream and provide signals that identify those anomalies.

In both algorithms, the tissue comprises a series of linked *cells*, each cell “grown” in response to specific data, in a data stream being input to the system. Cells grow and are supported by homogeneous data. Where data does not exist to support a cell, the cell dies. Where too much/too diverse data exists for a cell, the cell divides. Cells exist in a dynamic network structure, with similar cells linked or placed near to each other. The use of a cellular representation is also intended to enable distributed processing and the support of multiple datastreams simultaneously.

The network tissue algorithm explicitly maintains cells within a network data structure, where each cell stores a cluster of data items (or antigens). Cells are linked to each other in the network based on their similarity to each other. Antigens survive for a fixed period of time before being removed from a cell. Should a cell lose all of its antigens, it “dies” and a signal is produced indicating an anomaly. (If the input data is homogenous, cells should always have sufficient data to support them; only if the data changes will a cell die and hence indicate the anomaly.)

The swarm tissue algorithm also uses cells, but these cells are maintained as a swarm of moving agents. Each cell in this algorithm represents a single data item. Cells are attracted to and repelled from each other based on similarity. Cells live for a fixed period of time before being removed; if a cell is removed that has not formed part of a cluster, a signal indicating an anomaly is produced.

Both algorithms have been tested on standard machine learning data sets and show excellent accuracies of anomaly detection, while also providing the benefits of automatic adaptation in real-time to dynamically changing data.

Novel Robotics

In addition to investigations of bio-inspired algorithms capable of adaptation, another objective of MOBIUS was to examine how unusual or “smart” materials might be controlled and their characteristics exploited by such algorithms. Following early success with a prototype “snake robot”, UCL Ph.D. student Siavash Haroun Mahdavi developed novel robots capable of adapting to damage for MOBIUS. BAE Systems (formally British Aerospace) are now funding the creation of an autonomous snake robot with damage tolerance. As such, the hardware is owned by BAE Systems, but findings of Dr Peter Bentley are generated for the purposes of EOARD and the MOBIUS project.

The brief provided by BAE was to create a cheap, autonomous robot capable of being deployed in numbers, adapting to its terrain, and acting as antennas to enable the formation of a dynamic communications network.

Early on it was decided to focus on the use of shape memory alloys as actuators. Commonly known as “muscle wire”, the alloy returns to a trained state when heated (typically by passing a current through it). While production models would probably use alternative, newer alloys with less current demand, the principle of material property exploitation remains valid. In other words, the research focussed on the use of genetic algorithms to automatically learn the intrinsic properties of the materials used and exploit those properties in order to achieve locomotion, recovery from damage and reception of a radio signal.

The work has been very successful and has enjoyed substantial media coverage. It has been shown that a snake robot using shape memory alloys, in particular NiTi wires, could learn to move on different surfaces. A genetic algorithm was used to evolve a finite state machine capable of activating the actuators appropriately to induce motion. The work involved no modelling, analysis or prediction – by evaluating the evolving movement strategies in the actual robot, evolution automatically exploited the properties of the real robot. Because of this approach, extensive tests have shown that damage and disablement of the actuators is automatically compensated for by the GA, i.e., the robot is capable of recovering from damage by learning new movement strategies. Experiments demonstrated that a high percentage of locomotion can be recovered more than once, even when muscle wires crucial to a locomotion strategy are disabled.

Other work has involved the creation of an antenna, with morphological configuration controlled by the activation of NiTi wires. Again a genetic algorithm was used to evolve an activation configuration to attempt to adapt the antenna shape in order to maximise its reception of a transmitted signal. Experiments demonstrated the GA could discover a noise tolerant antenna that minimised the effect of noise on the system. Analysis showed that the antenna was capable of adapting to very specific noise environments. This is the first work to demonstrate an antenna capable of adapting to specific noise conditions. It seems likely that these ideas will be highly beneficial in numerous applications.

This strand of work will continue beyond the end of the MOBIUS. The final prototype robot is under development at the time of writing and will combine both elements of snake robot with adaptive antenna into a single device. There has recently been an invitation to show the device in the robot section at the Royal International Air Tattoo, 2005. It should be noted that the robot is mainly a testbed for investigating how adaptive algorithms can exploit materials that may be difficult to analyse. A useful robot must also incorporate improved actuators and the addition of sensors and other methods to direct its motion intelligently.

Self-Assembling Systems

A final goal of MOBIUS was to investigate self-building systems. Designed and controlled by evolutionary development algorithms, such technology would not only adapt and repair itself, it would construct itself from smaller components. Work with materials scientists identified several new materials suitable for exploitation by the developmental algorithms. One cheap and widely available material is *ferrofluid* – a “magnetic fluid” that can be reshaped by magnetic fields. Combined with other new liquids that have adjustable viscosities depending on an electric current passed through them, it is theoretically possible to shape and solidify forms at all scales (although larger scales require significant magnetic fields). Potentially such a technology could enable three-dimensional circuits or other forms to be grown or repaired. However, costs of further investigation precluded the construction of a prototype.

Instead, a cheaper method of self-building was investigated by a UCL research student Navneet Bhalla supervised by Peter Bentley. In this work, the objective was to enable the self-assembly of a desired two-dimensional form, out of predesigned components. The components would be evolved automatically using a computer model to analyse their effectiveness, then constructed using rapid prototype technology (stereolithography). The initial prototype used magnetism to provide an attractive and repulsive force for each component. Energy was provided by agitating the surface on which the components are randomly placed. The work has so far been a partial success – evolution has yet to be fully exploited in the design process, but hand-designed components do indeed self-assemble into a desired larger form when agitated. This work will now be taken further by the research student, who is intending to do his doctorate on the topic, based at Calgary University. The eventual aim is to create a three-dimensional self-assembling system, with all components

automatically evolved and created using “3D printers”. 3D printer technology already permits printing of three-dimensional forms of different colours and materials, so the potential for self-assembling three-dimensional circuits, batteries, sensors and actuators is very real.

PUBLICATIONS

Fractal Development Algorithm:

- [1] Bentley, P. J. (2005) Evolving Fractal Gene Regulatory Networks for Graceful Degradation of Software. Chapter in Babaoglu, O., Fetzer, C., Jelasity, M., Leonardi, S., Montresor, A., van Moorsel, A., van Steen, M. Self-* Properties in Complex Information Systems. Springer Lecture Notes in Computer Science. [BECH6] (Extended version of abstract presented at First International Symposium on Cellular Computing (CELLCOM04), December 09-10th 2004, Centre for Scientific Computing, University of Warwick.)
- [2] Bentley, P. J. (2004) Controlling Robots with Fractal Gene Regulatory Networks. Chapter in de Castro, L. and von Zuben, F. (editors) Recent Developments in Biologically Inspired Computing. Idea Group Inc.
- [3] Bentley, P. J. (2003) Evolving Fractal Gene Regulatory Networks for Robot Control. In Proc. of the European Conference on Artificial Life (ECAL 2003). W. Banzhaf, T. Christaller, P. Dittrich, J. T. Kim and J. Ziegler (eds), Springer-Verlag Berlin Heidelberg: Berlin, pp.753-762.
- [4] Bentley, P. J. (2004) Adaptive Fractal Gene Regulatory Networks for Robot Control. In Miller, J. (Ed.) Workshop on Regeneration and Learning in Developmental Systems, Genetic and Evolutionary Computation Conference (GECCO 2004).
- [5] Bentley, P. J. (2004) Fractal Proteins. In Genetic Programming and Evolvable Machines Journal, Kluwer Academic Publishers, London. v5, 71-101.
- [6] Bentley, P. J. (2004) Evolving Beyond Perfection: An Investigation of the Effects of Long-Term Evolution on Fractal Gene Regulatory Networks. BioSystems v76, 291-301. Extended version of:
- [7] Bentley, P. J. (2003) Evolving Beyond Perfection: An Investigation of the Effects of Long-Term Evolution on Fractal Gene Regulatory Networks. In Proc of Information Processing in Cells and Tissues (IPCAT 2003). Swiss Federal Institute of Technology. Lausanne, Switzerland, pp.449-460.
- [8] Bentley, P. J. (2003) Evolving Fractal Proteins. In Proc of ICES '03, the 5th International Conference on Evolvable Systems: From Biology to Hardware. A. Tyrrell, P. Haddow, and J. Torresen (eds), Springer LNCS 2606, Berlin, pp. 81-92.

Fractal immune system:

- [9] Bentley, P. J. and Timmis, J. (2004) A Fractal Immune Network. In Proc. of The Thirds international Conference on Artificial Immune Systems (ICARIS 2004), Catania, Sicily. September 2004. Springer Verlag LNCS 3239, pp.133-145.

Tissue Algorithms:

- [10] Bentley, P. J., Ujjin, S., Greenfield, J. (2005) “Two Ways to Grow Tissue for Artificial Immune Systems” Submitted to The Fourth International Conference on Artificial Immune Systems (ICARIS 2005).

Novel Robots:

- [11] Haroun Mahdavi, S. and Bentley, P. J. (2005) Innately adaptive robotics through embodied evolution. Submitted to Journal of Autonomous Robotics. Extended version of:
- [12] Haroun Mahdavi, S. and Bentley, P. J. (2005) Innately adaptive robotics through embodied evolution. In Proc. of Robosphere 2004, the 2nd Workshop on Self-Sustaining Robotic Systems, NASA Ames Research Center, Nov 9-10, 2004.
- [13] Haroun Mahdavi, S. and Bentley, P. J. (2003) Evolving Noise Tolerant Antenna Configurations using Shape Memory Alloys. In Proc of the Second International Conference on Computational Intelligence, Robotics and Autonomous Systems (CIRAS 2003),. December 15-18 2003, Singapore.

- [14] Haroun Mahdavi, S. and Bentley, P. J. (2003) An Evolutionary Approach to Damage Recovery of Robot Motion with Muscles. In Proc. of the European Conference on Artificial Life (ECAL 2003). W. Banzhaf, T. Christaller, P. Dittrich, J. T. Kim and J. Ziegler (eds), Springer-Verlag Berlin Heidelberg: Berlin, pp.248-255.
- [15] Haroun Mahdavi, S. and Bentley, P. J.(2003) Evolving Motion of Robots with Muscles. In Proc. of EvoROB2003, the 2nd European Workshop on Evolutionary Robotics, EuroGP 2003. pp. 655-664.

Self-assembling systems:

- [16] Bhalla, N. (2004) Self-assembling systems in two dimensions. M.Sc. (Intelligent Systems) project report. Department of Computer Science, University College London. Supervisor: P. J. Bentley.

General concepts (arising indirectly from MOBIUS):

- [17] Bentley P. J. (2005) Climbing Through Complexity Ceilings. Invited presentation at Symposium on Distributed Form: Network Practice. University of California, Berkeley, USA. October 22-24, 2004. To appear in post-published proceedings.
- [18] Bentley, P. J. (2004) Software Seeds: The Garden Where Perfect Software Grows. Feature in New Scientist. 6 March. Reed Business Information Ltd. (London). pp. 28-31
- [19] Kumar, S. and Bentley, P. J. (Contributing Eds.) (2003) *On Growth, Form and Computers*. Academic Press, London.

CONCLUSIONS

During the course of the research, the following general findings have been made:

1. *Automatic exploitation of complexity* can be achieved through the use of bio-inspired computer algorithms. Evolutionary computation can learn to exploit unknown intrinsic properties of real materials (e.g. in the robot snake and antenna). Evolutionary developmental algorithms and algorithms based on tissue growth can exploit mathematical complexity produced by fractal equations and show performance enhancements (e.g. in fault tolerance, control, evolvability, and clustering).
2. *Self-design* can be achieved through the same techniques. Given functional requirements, evolution can automatically design solutions that satisfy those requirements (e.g. in robot control, function regression and clustering).
3. *Self-assembly* can be achieved to a limited extent through the evolution of components that selectively adhere to each other to form a desired final form. Technology limits the capacity of this self-assembly to highly simple forms at present.

In the immediate future, the gains from this technology are likely to be made in automatic learning systems that adapt to variable environments and recover from damage. Autonomous units, especially robots, would gain from fault-tolerant structures and controllers. Mission critical software could also gain from self-tolerance and adaptation. The key novelty is not that such systems could be given a degree of fault-tolerance, it is the method by which the fault tolerance is achieved: the systems learn to exploit whatever environment and resources are currently available in order to maximise performance at any given time.

This technology is still young and further development is required before it can be considered ready for use.

Dr. Peter J. Bentley

Department of Computer Science
University College London
P.Bentley@cs.ucl.ac.uk

Any opinions, findings and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the European Office of Aerospace Research and Development, Air Force Office of Scientific research, Air Force Research Laboratory.

APPENDICES

Fractal Development Algorithm:

“Fractal Proteins” published in the Journal of Genetic Programming and Evolvable Machines.

Downloadable at: <http://www.cs.ucl.ac.uk/staff/P.Bentley/BEJ2.zip>

“Investigations into Graceful Degradation of Evolutionary Developmental Software” to appear in the Journal of Natural Computing.

Downloadable at: <http://www.cs.ucl.ac.uk/staff/P.Bentley/BEJ3.pdf>

Fractal Immune System:

“A Fractal Immune Network”. In Proc. of The Third International Conference on Artificial Immune Systems (ICARIS 2004).

Downloadable at: <http://www.cs.ucl.ac.uk/staff/P.Bentley/BETIC1.pdf>

Tissue Algorithms:

“Two Ways to Grow Tissue for Artificial Immune Systems” Submitted to The Fourth International Conference on Artificial Immune Systems (ICARIS 2005).

Downloadable at: <http://www.cs.ucl.ac.uk/staff/P.Bentley/BEGRUJC1.pdf>

Novel Robotics:

“Innately Adaptive Robotics through Embodied Evolution” (short version presented at NASA Robosphere 2 conference) full version under review for Journal of Autonomous Robotics.

Downloadable at: <http://www.cs.ucl.ac.uk/staff/P.Bentley/MABEJ1.pdf>

General concepts/future needs and requirements:

“The garden where perfect software grows” New Scientist feature.

Viewable at: <http://www.cs.ucl.ac.uk/staff/P.Bentley/seedsarticle.html>

“Climbing Through Complexity Ceilings” Position paper to appear as chapter in book “Distributed Form, Network Practice”

Downloadable at: <http://www.cs.ucl.ac.uk/staff/P.Bentley/BES6.pdf>